Appendix X. *Deepwater Horizon* Blue Pod AMF System Batteries

Introduction

This appendix describes the condition of the blue pod automatic mode function (AMF) system when it was examined on July 5, 2010, and discusses the impact of this condition on the ability of the control system to initiate an AMF sequence on demand.

Transocean and Cameron tested the AMF system in the blue pod's subsea electronic modules (SEMs) A and B on July 5, 2010. The results of the test indicated that the blue pod would not have been able to initiate the AMF sequence to close the high-pressure blind shear ram (BSR).

Background

The AMF system on *Deepwater Horizon* BOP control system was powered by non-rechargeable primary cell batteries. There were two SEMs in each pod. Each SEM had an AMF card powered by a dedicated 9-volt battery pack. (All voltages associated with the AMF system were direct current.)

Each 9-volt battery pack consisted of twelve, 3-volt lithium manganese dioxide (Li-MnO_2) battery cells. (Refer to Figure 1.) When new, each battery pack had a design life of 42 Ah.

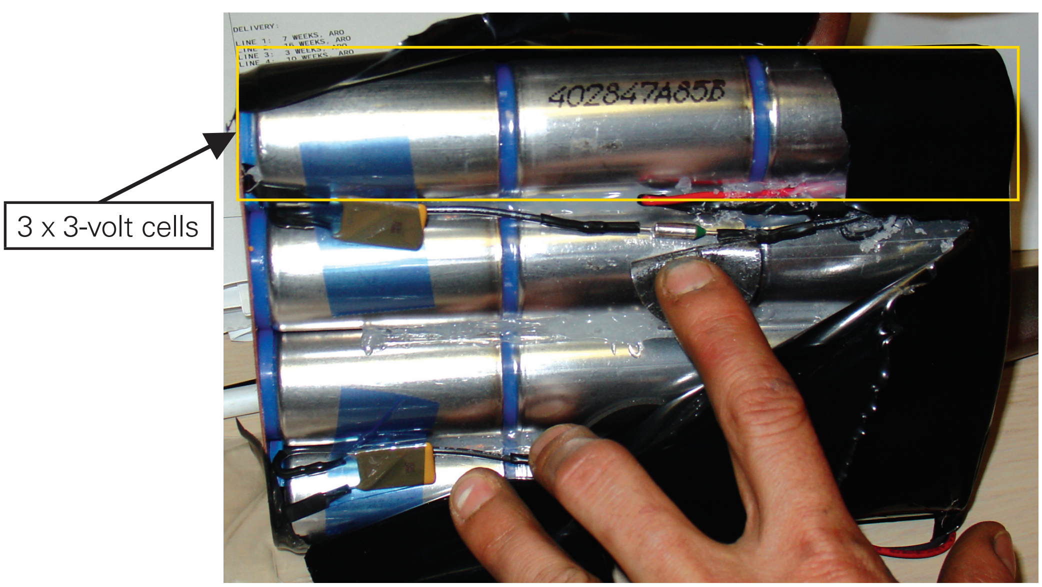

Figure 1. 9-volt AMF Battery Pack (Showing 4 Sets of 3 x 3-volt Cells) (Typical SAFT Battery Pack–not *Deepwater Horizon*).

The third set of AMF batteries in each pod was the 27-volt AMF battery bank. This battery bank consisted of three 9-volt battery packs connected in series to provide 27 volts when fully charged. The purpose of this battery bank was to provide power to 24-volt rated relays on the AMF card, the ambient (hydrostatic head at seabed) and conduit pressure sensors, and the SEM programmable logic controller (PLC) solenoid output modules.

AMF Operation

The AMF sequence is designed to close the high-pressure BSR automatically in the event that communications and electrical and hydraulic power are lost to each SEM. This can occur upon loss of both the multiplex (MUX) cables and the hydraulic line.

When the AMF system is armed from the surface, a digital signal is sent from each SEM to its respective AMF card to operate a bi-stable relay, whose closed contacts connect the 9-volt battery pack to the AMF controller, allowing it to function. Once powered, the AMF card sends a signal back to the SEM, indicating that the AMF card is active.

Each AMF controller monitors pulsed signals, generated from the yellow and blue pod SEMs. Loss of both electrical power and communications to all four SEMs would stop the pulsed signals. Upon detection of this condition, the AMF controller activates a 24-volt relay on the AMF card. This relay connects the 27-volt battery bank to two AMF pressure sensors.

The AMF controller compares the values of the ambient and conduit pressure sensors. If the pressures are outside of a pre-determined tolerance, the AMF controller activates an additional 24-volt relay, which switches the 27-volt battery bank to power the SEM PLC solenoid output modules. At the same time, a third 24-volt relay is energized. This relay switches a 5-volt power supply to the SEM central processing unit (CPU) via the VMEbus (VERSAmodule Eurocard bus) and initiates a reboot of the SEM CPU. The 5-volt supply is regulated by the 9-volt AMF card battery pack. If the AMF system is armed upon CPU reboot, the SEM executes the pre-programmed AMF sequence. The 24-volt AMF card relays are powered by the 27-volt batteries.

Once the AMF sequence is completed, the SEM powers down the AMF controller by sending a signal to the bi-stable relay to open the relay output contacts, powering down the AMF card and causing the SEM to power down as well. This final action isolates both the AMF card battery and the AMF battery bank, stopping further battery discharge.

Blue Pod Tests

Examination of the blue control pod by Transocean and Cameron, when the pod was retrieved on July 3-5, 2010, revealed problems with the AMF system.

In preparation for the AMF test on the blue pod, the Cameron PETU (Portable Electronic Test Unit) was connected to SEM A. The PETU can only provide power to the SEM to which it is connected. The SEM A AMF system was then armed by the operator. Enerpac pressure pumps were used to apply test pressures on the ambient and conduit pressure sensors: 2600 psi on the ambient pressure sensor and 8000 psi on the conduit pressure sensor.

Power was turned off to SEM A. This simulated a loss of electrical power and communications. After 30 seconds, the conduit sensor test pressure was lowered to the ambient test pressure of 2600 psi. The AMF sequence should have started within 15 seconds. However, 3.5 minutes after the AMF input conditions were met, the AMF had not fired. Power was re-applied to SEM A, and the AMF sequence fired.

The blue pod test log from Transocean has the following entries pointing to problems with the AMF batteries:

> 7/5/2010 10:04-10:27 "Performing check on Blue Pod on A and B SEM for the Sub Sea Electronics Module Test, as per Cameron procedure, perform [AMF] test and failed watt the time at 3.5 minutes did not fire [AMF], once we put the power back on the PETU the [AMF] fired, on SEM A." (This is a direct quote and means that the test team waited for 3.5 minutes after performing the AMF test and the AMF sequence still did not fire.)
>
> 7/5/2010 10:27-11:27 "Review drawings # SK-122178-21-06. Perform Battery check on 9 and 27 volt with a new calibrated meter (Fluke Type 115 RMS MultiMate Serial #12990354 Item #2538790 (1) GAH9. The SEM A 9 volt reading 8.78 volts SEM B 9 volts reading .142 volts reading on the 27 volt 7.61 . . . the Transocean person checking the Battery, ET Supervisor."

The conclusion of the tests on the blue pod was that the AMF systems on both SEMs, A and B, were inoperable on July 5, 2010. The cause of the failure was insufficient battery voltage on the 27-volt AMF battery bank which powers critical functions on both SEMs A and B. The measured voltage on the 27-volt battery bank that was 7.61 volts.

Further AMF Tests

The investigation team subsequently performed a number of tests on a representative Cameron AMF system in a Mark I SEM to supplement the results reportedly obtained from the blue pod test performed by Transocean and Cameron.

These tests established that 7.61 volts on the 27-volt AMF batteries was insufficient to operate any of the three 24 volt rated relays on the AMF card. These relays are required to switch battery voltage to the pressure sensors, the SEM CPU, and the SEM solenoid valve output modules. The tests establish the voltages required to energize the various relays and solenoid valves associated with the AMF sequence. (Refer to *Table 1*).

Table 1. Required Voltages for a Cameron AMF Card.

27-volt Battery Load	Voltage Required to Energize
AMF sensor relay: energizes when the AMF card detects a loss of electrical power and communications.	14.4 volts
CPU relay: energizes when all AMF input conditions are met and switches 5 volts to the SEM CPU.	14.6 volts
Solenoid relay: energizes when all AMF input conditions are met and switches 27 volts to the SEM solenoid output module.	14.9 volts
Solenoid coils: five solenoids are required to complete the AMF sequence. The SEM CPU controls the solenoid valve sequence.	15.9 volts to 20 volts for each solenoid

Failure to fully energize either of the relays that provide power to the SEM (either 5 volts or 27 volts) would prevent the AMF sequence from completing successfully.

The test results can be used to better understand the observations recorded at the July 2010 blue pod test. When the initial AMF condition of loss of power and communications was met, the working SEM A AMF controller should have switched the 27-volt AMF battery bank to power the conduit and ambient pressure sensors. As this battery bank was only at 7.61 volts, the relay, which required a minimum voltage of 14.4 volts, could not have been energized, and the AMF sequence would have frozen at that point.

When the PETU power was re-applied to the SEM after 3.5 minutes, 24 volts were immediately applied to the AMF relay, which applied power to the AMF sensors and satisfied the final AMF input condition. The AMF controller then activated the 5-volt relay powering the SEM CPU and, at the same time, switched 27 volts to the SEM PLC output module. The SEM rebooted as a result of having PETU power applied. It detected that the AMF board was armed and assumed that the AMF card rebooted it. The SEM performed its own checks and then ran the AMF sequence.

Had the 27-volt batteries been able to supply sufficient power to the AMF relays, the AMF sequence would have activated within 15 seconds of meeting the AMF input conditions. (Refer to Figure 2 for the condition of the AMF system.)

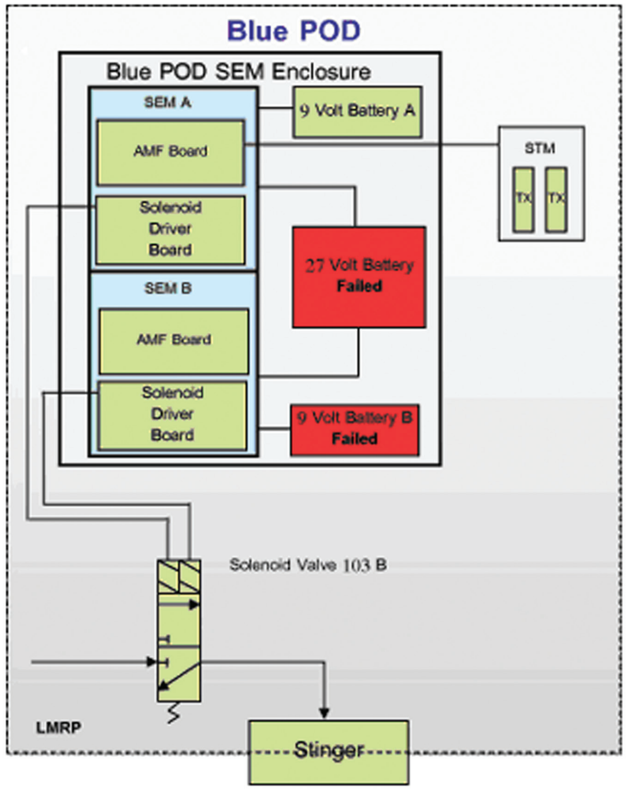

Figure 2. Condition of the AMF System as Found upon Recovery of the Blue Pod.

Determination of the Condition of the Blue Pod AMF System at the Time of the Accident

At the time of the accident, the SEM B AMF system would have been inoperable due to an extremely low voltage battery condition (0.142 volts). As mentioned previously, this represented a loss of AMF redundancy. The load on the remaining SEM upon initiation of the AMF sequence would have been higher, since it required more voltage for a single SEM to energize one coil of a two-coil solenoid than if both SEMs were to energize both coils.

The SEM A AMF controller would have been operable due to the healthy state of the 9-volt battery pack. Upon loss of electrical power and communications, the 27-volt battery bank, which was measured at 7.61 volts on July 5, 2010, would have been switched to power the ambient and conduit pressure sensors. As stated in the previous section, this would have been insufficient to power any of the AMF relays, and the AMF sequence would have frozen.

If the 27-volt battery bank had sufficient charge at the time of the accident, the sequence would have been completed successfully, and the 27-volt battery would be in a charged condition at the time of examination. As the 27-volt bank had not changed at the time of examination, it most likely had insufficient charge at the time of the accident.

AMF Battery Design

Figure 3 illustrates the discharge curve for a SAFT LM33550 Li-MnO2 battery. This battery has similar discharge characteristics to the 27-volt battery banks used by Cameron in their MK II SEMs. The data was adapted from a C/120 load at 20°C.

Li-MnO2 is a high-energy battery cell. It is stable at room temperature and has a shelf life of 6 years at that temperature.

Above room temperature, the discharge rate under both load and no-load conditions increases. For calculating battery usage, Cameron used the following discharge rates:

- 2% per year in storage.
- 5% per year inside the SEM subsea.
- 30% per year inside the SEM on the surface.

Cameron recommends replacing AMF batteries after 5 years in storage.

Figure 3 shows the estimated battery usage for one year. This value was calculated with an assumed usage: 1 year in storage, 3 months of surface operation, 9 months of subsea operation and 33 AMF sequences with five solenoid valves.

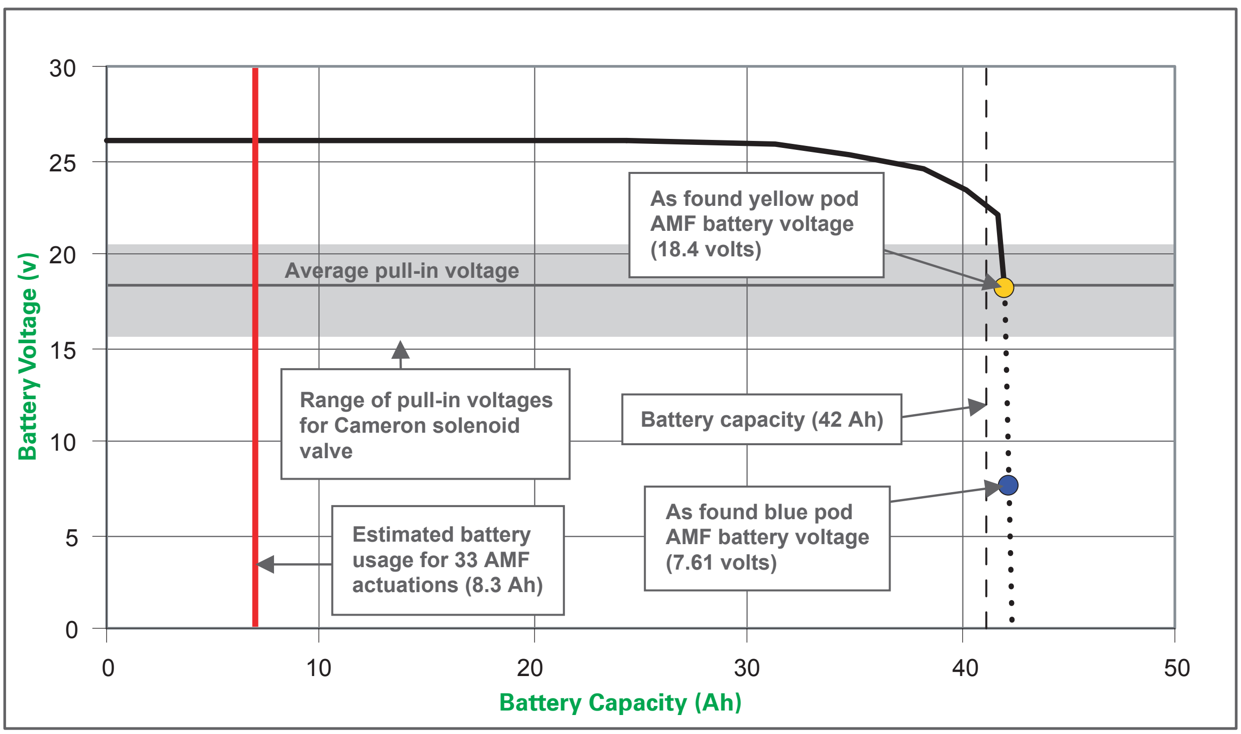

Figure 3. Discharge Curve of a SAFT LM33550 Battery.

Subsequent tests by the investigation team on representative solenoid valves from a Cameron Mark II control module confirmed that the pull-in voltage is 15 volts in air. The two coils in the tested device gave virtually identical results. The solenoid pulled in between 14.7 volts and 15.2 volts. The solenoid plunger then dropped out between 2.2 volts and 2.4 volts with no hydraulic pressure on the fluid end of the valve. Further testing was conducted on five representative Cameron solenoid valves with 3,000 psi hydraulic pressure present. For the AMF batteries to have powered the AMF sequence, they would have required a minimum voltage of 15.8 volts and sufficient battery charge to power the five solenoid valves under that pressure. *Figure 3* demonstrates the range (15.8 volts to 20.10 volts) and average (17.9 volts) voltage required to energize one solenoid valve.

Conclusion

Based on the information provided, the investigation team concluded that the AMF system or AMF controller could not have closed the high-pressure BSR because the reported charge of 7.61 volts on the 27-volt AMF battery bank would have been insufficient to power the AMF relays. It would also have been insufficient to operate the high-pressure BSR solenoid valve.